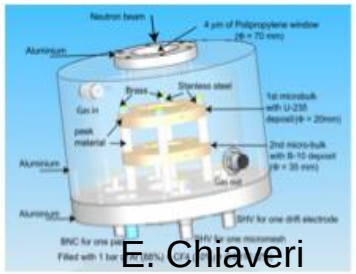
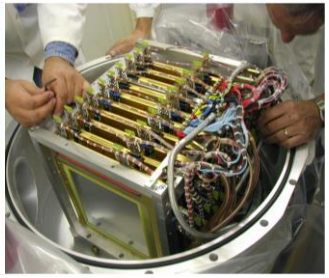
The n_TOF Collaboration,
http://www.cern.ch/nTOF

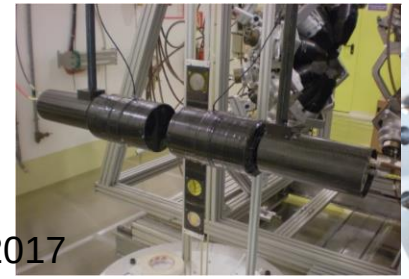
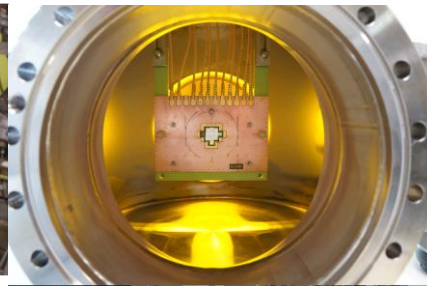
The n_TOF facility: neutron beams for challenging measurements at CERN

Enrico Chiaveri

Spokesperson of n_TOF Collaboration





What is n_TOF?

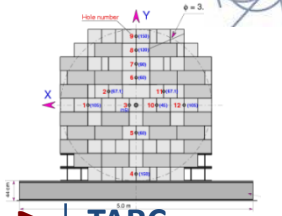
> The goal of the nTOF is to provide unprecedented precision in neutron kinetic energy determination, which will in turn bring much-needed precision in neutron-induced cross-section measurements. Such measurements are vital for a range of studies in fields as diverse as nuclear technology, astrophysics and fundamental nuclear physics. The nTOF will provide neutron rates some three orders of magnitude higher than existing facilities, allowing measurements to be made more precisely and more rapidly than in the past.
>
> CERN COURIER July 2nd 2001

- **The n_TOF Collaboration was founded in 2001.**
- **Members as of September 2016:**
  - **42 Institutions (from EU, US, IN, JP, RU and AU)**
  - **117 scientists**
  - **2 experimental areas at CERN (EAR1, EAR2 since 2014)**

Motivations for neutron cross section measurements @ n_TOF

- Nuclear Waste Transmutation
- Medical Application
- Astrophysics
- Nuclear Physics

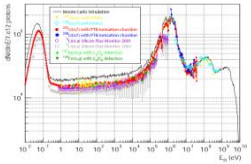
n_TOF Timeline



1995-1997 **TARC** experiment

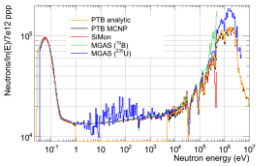
May 1998 **Feasibility** CERN/LHC/98-02+Add

2000 **Commissioning**



2004-2007 **Problem** Investigation

May 2009 **Commissioning**



2010 **Upgrades:** Borated-H_2O Second Line Class-A

2014-2016 **Phase III** Capture: 14 Fission: 4 (n,cp): 4

July 2014 **Commissioning of EAR-2**

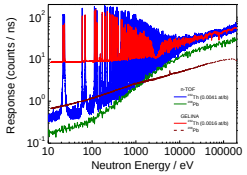
1996 — **2016**

1997 **Concept** by C.Rubbia CERN/ET/Int. Note 97-19

Aug 1998 **Proposal** submitted

1999 **Construction** started

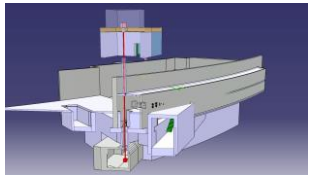
2001-2004 **Phase I** Isotopes Capture: 25 Fission: 11



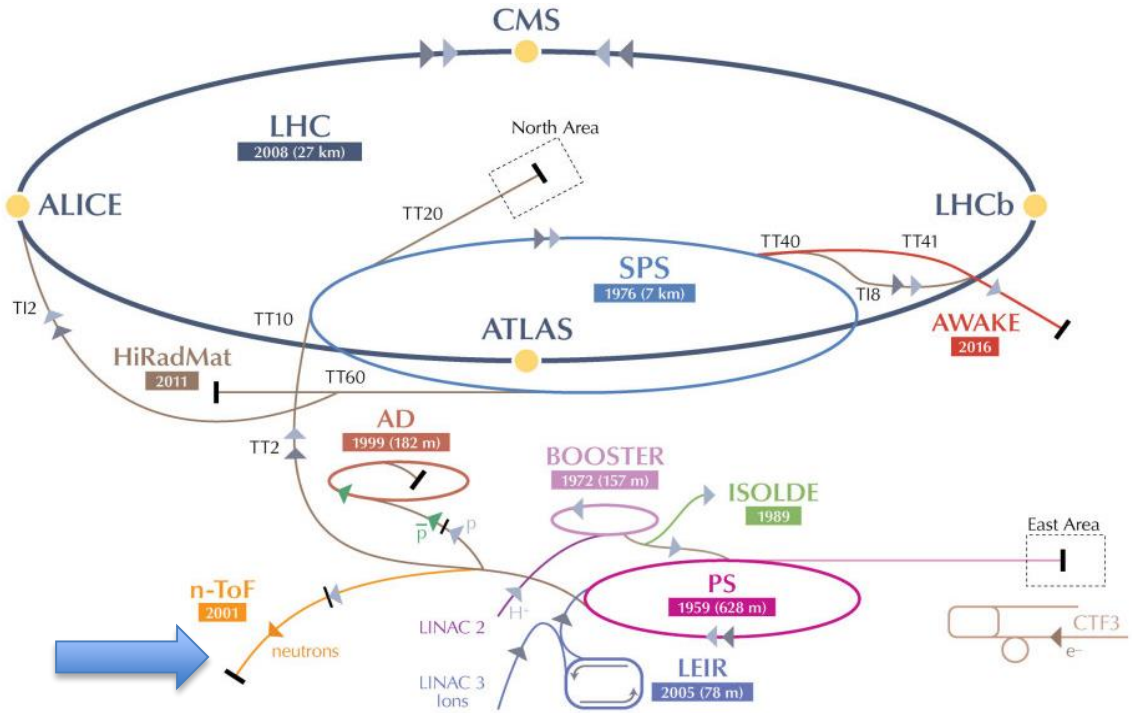
2008 **New Target** construction

2009 - 2012 **Phase II** Isotopes Capture: 14 Fission: 3 (n,cp): 2

2011 **EAR2** Design and Construction

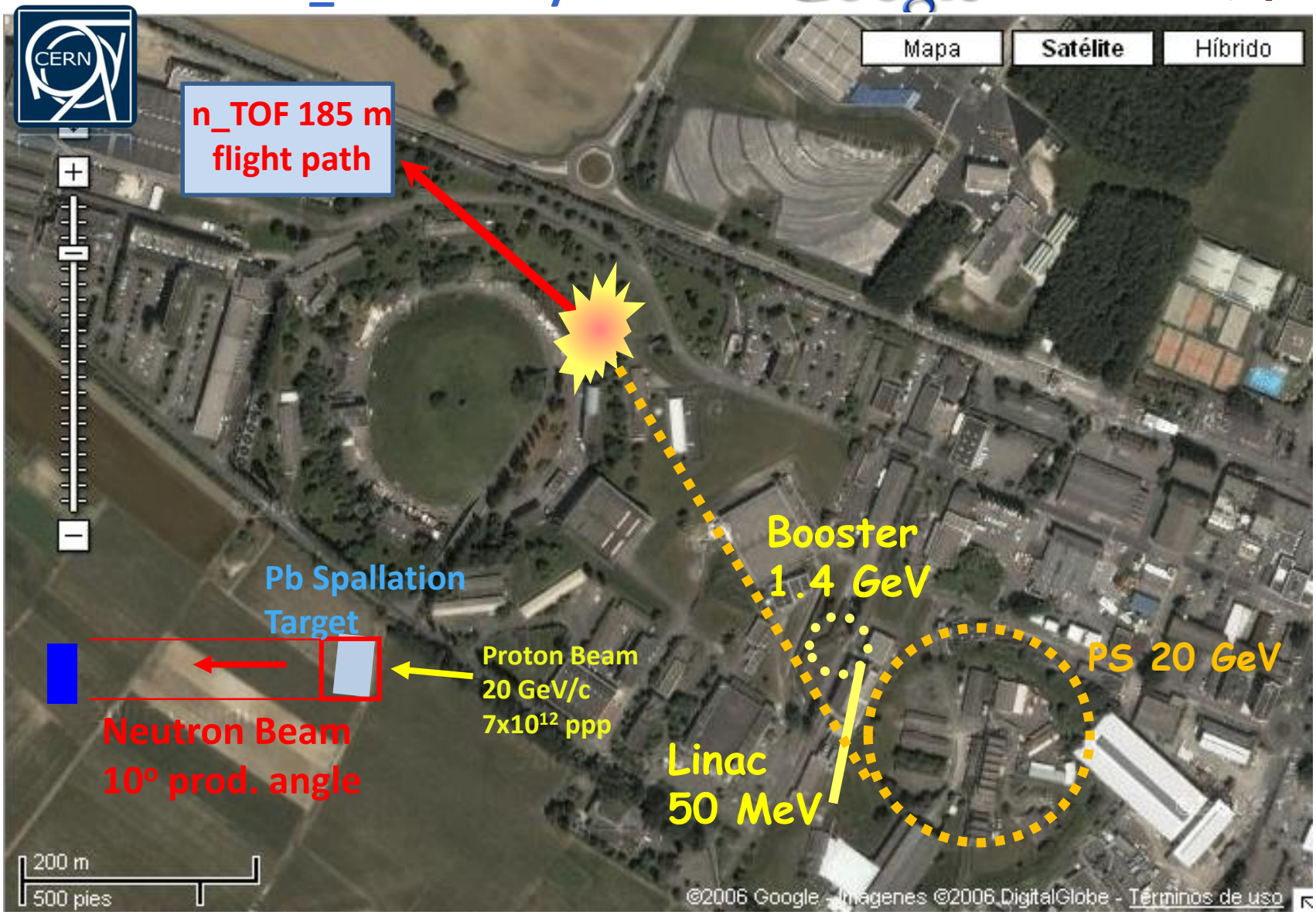


n_TOF: A spallation neutron source using the PS 20 GeV/c prot. beam

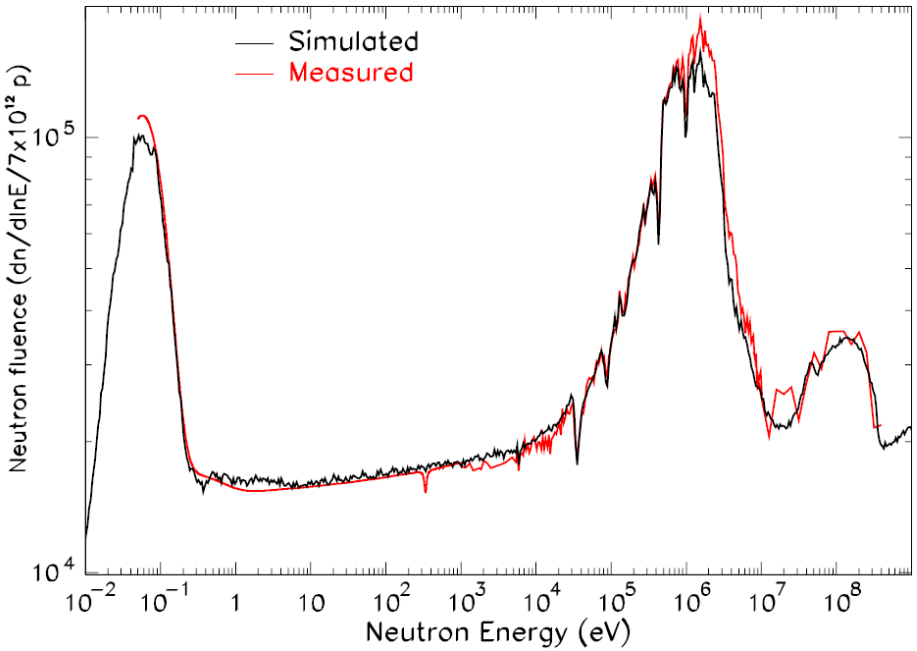


C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

The n_TOF Facility at CERN: Google a view



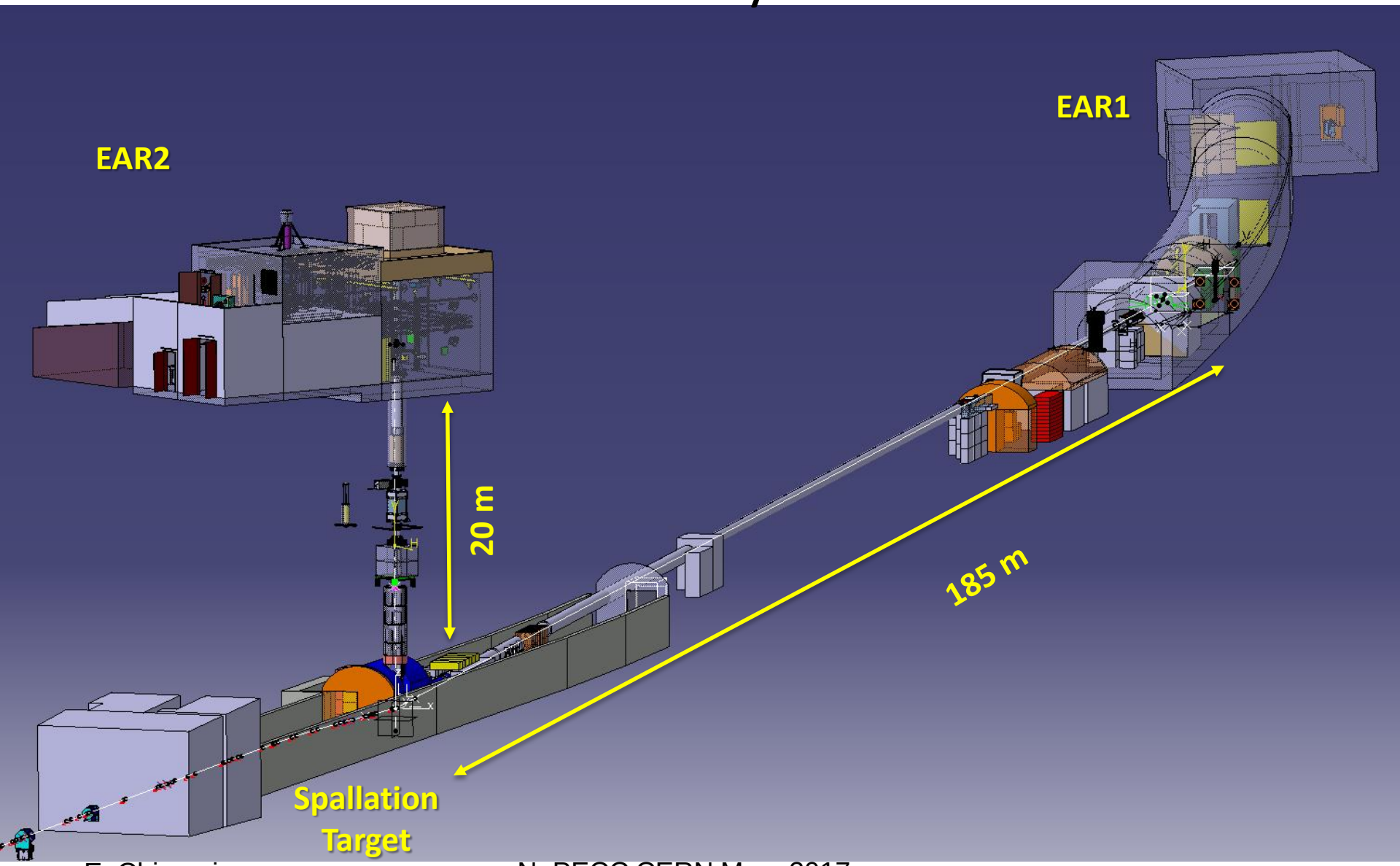
The n_TOF facility



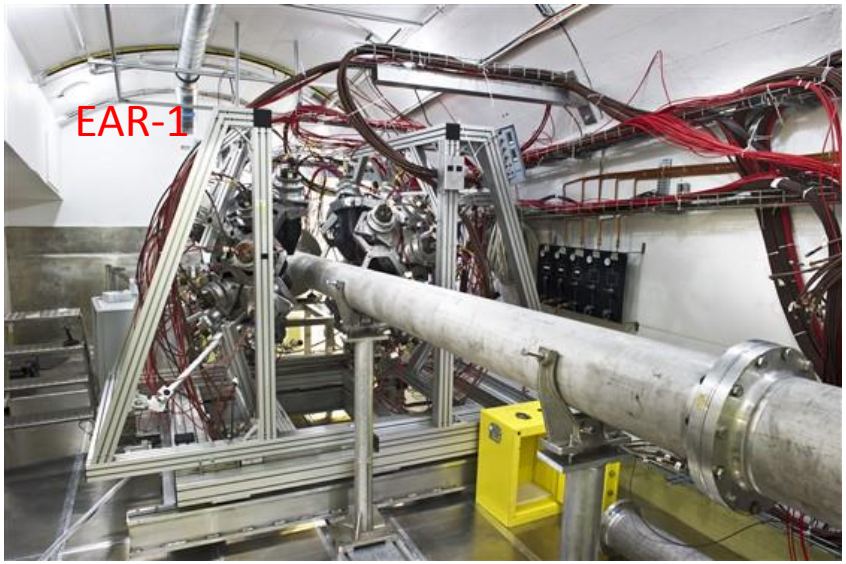
- Main feature of n_TOF is the extremely high instantaneous neutron flux (10^5 n/cm^2/pulse)
- Unique facility for measurements of radioactive isotopes (maximize S/N)
  - Branch point isotopes (astrophysics)
  - Actinides (nuclear technology)

- Other features of the neutron beam:
  - High resolution in energy ($\Delta E/E=10^{-4}$) → study resonances
  - Large energy range (25 meV<E_n<1 GeV) → measure fission up to 1 GeV
  - Low repetition rate (<0.8 Hz) → no wrap-around

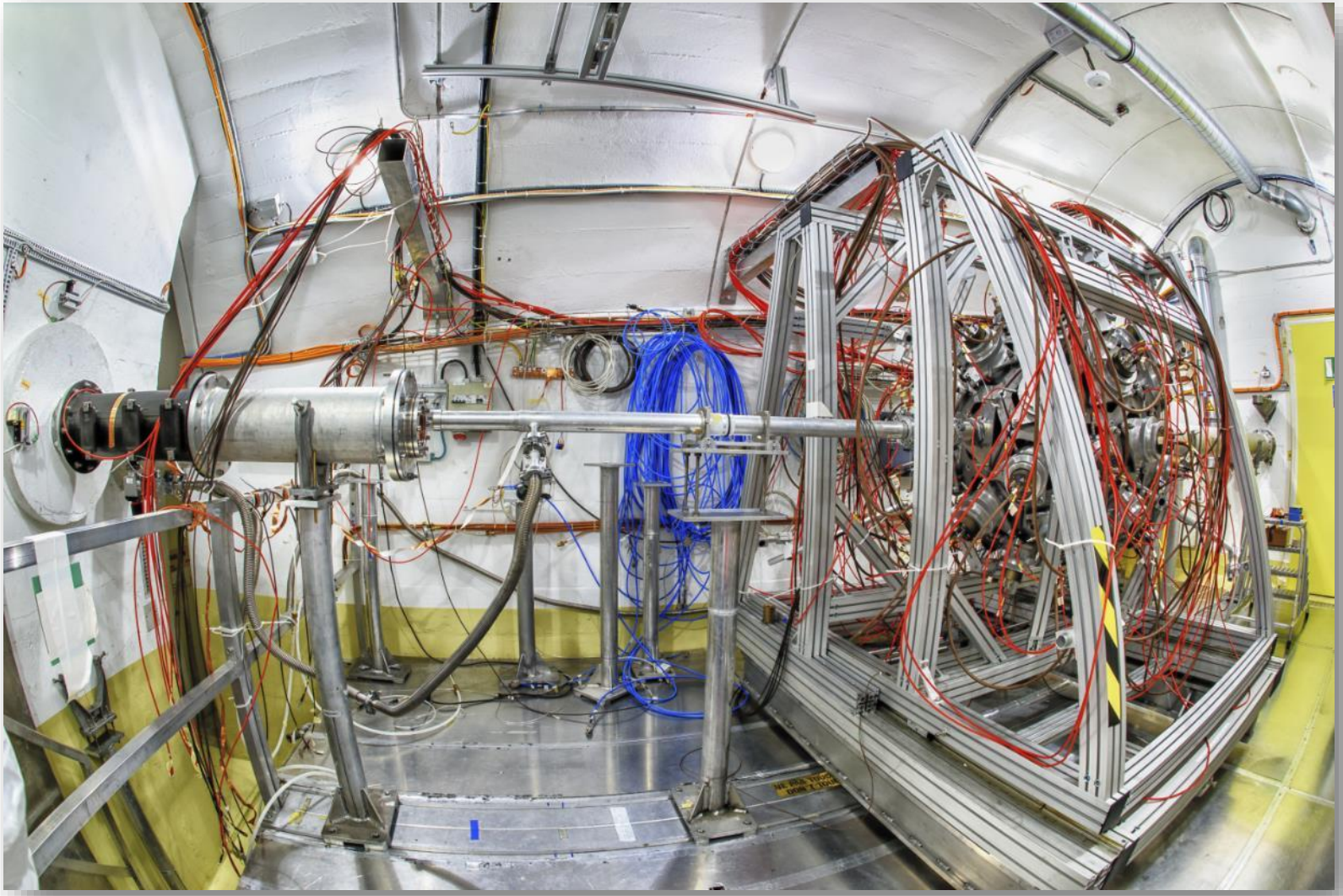
The Neutron Time Of Flight Facility



N_TOF Beam Line



The neutron Time Of Flight Facility: EAR1



n_TOF Data Acquisition System

- High instantaneous neutron flux
  - Several events for each neutron pulse expected + pile-up between
- Standard DAQ methods was largely inadequate at the beginning of experiment

- n_TOF DAQ based on **flash-ADC**:
  - **2001** 100 fADC channels (8bit), up to 1 GS/s
    Full history of every detector digitized during time window of up to 80 ms
  - **2014** 132 fADC channels (12bit/14bit),up to 1.8 GS/s

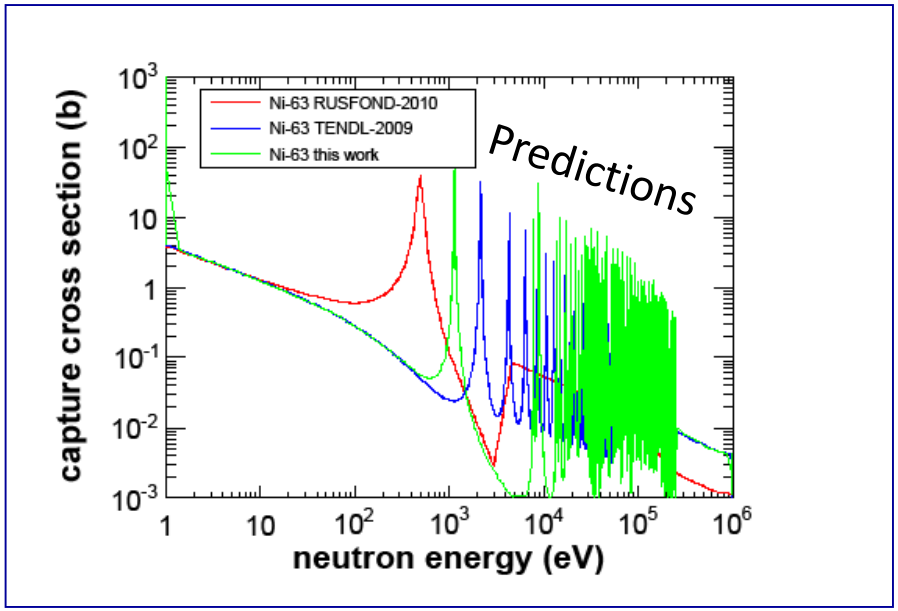
- Offline signal reconstruction for time and charge
  - Pulse-shape fitting analysis (pile-up)
  - Simple algorithm for single signals

EAR1 examples: ^{63}Ni(n,γ)

^{63}Ni (unstable) represents first branching point in s-process reaction path:
→ Highest uncertainty in ^{63,65}Cu abundances comes from unknown ^{63}Ni(n,γ) cross section

Until 2011, measurements so far ONLY at thermal energies:

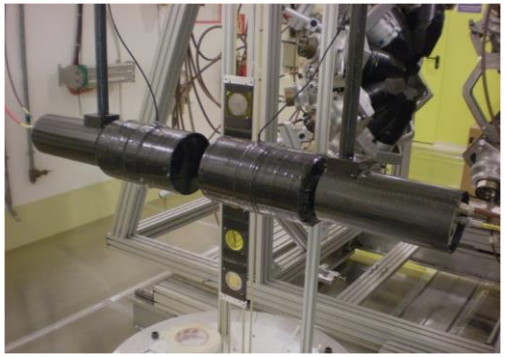
- MACS are based on extrapolation of these cross sections from theoretical
- MACS at 30 keV:
  - KADoNiS: 31± 6 mb
  - TENDL(2009): 68.9 mb
  - Mengoni (th): 90.8 mb

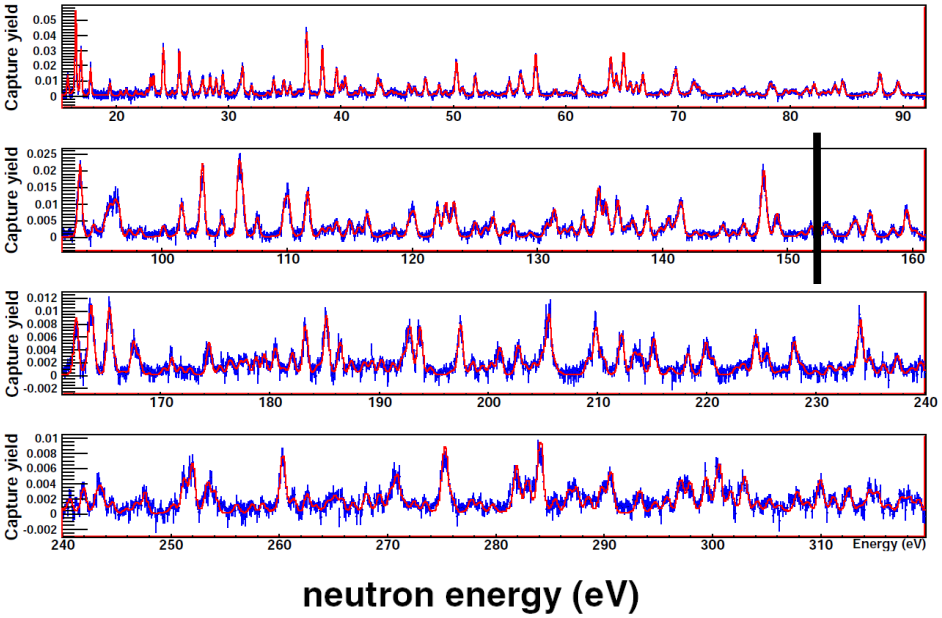


The raw material is similar to the one measured at DANCE (LANL), but chemical purification (PSI@Switzerland) has been carried out in order to eliminate the 2% Cu impurities:
now "just " ^{62}Ni and ^{63}Ni (12%, 112 mg).

EAR1 examples: ^{241}Am(n,γ)

Half-life: **432 y**
Sample: **32.2 mg**
Activity: **3 GBq**





Measurements made with both **C_6D_6** and **TAC** detectors, to minimize systematic uncertainties.

- First time that complete region is covered **from thermal to MeV** in a single measurement.
- Unprecedented resolution and statistics, to **extend RRR** above 150 eV, up to 320 eV.

The n_TOF Facility (2014)

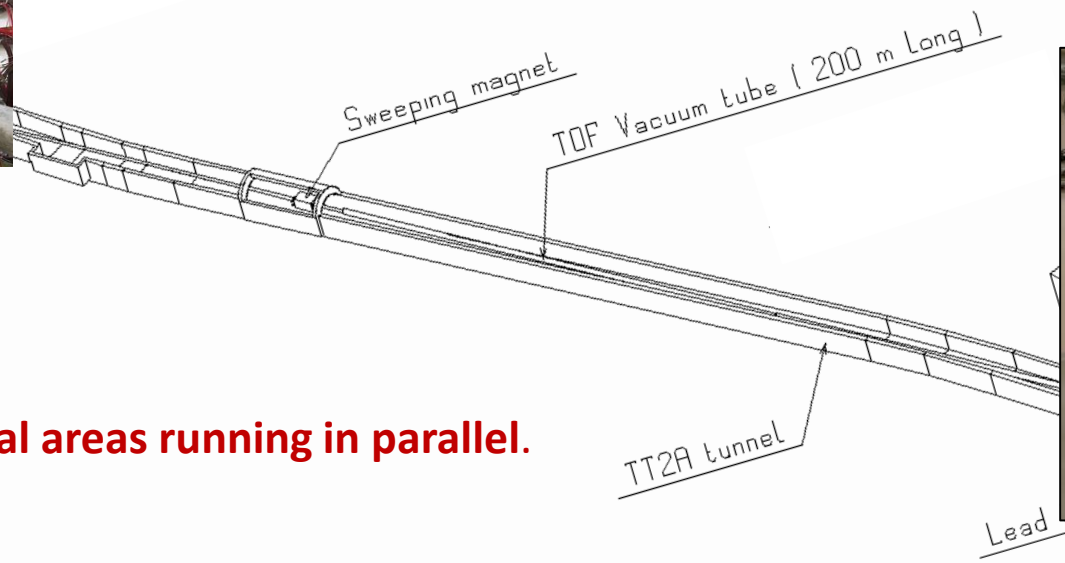
Two experimental areas (EAR):

- Horizontal flight path:
  EAR1 at **182.5 m**
- Vertical flight path:
  EAR2 at **18.2 m**

Both beam lines have:

- 1st collimator:
  halo cleaning + first beam shaping.
- Filter station.
- Sweeping magnet.
- 2nd collimator: beam shaping.

EAR1



EAR2

Two experimental areas running in parallel.

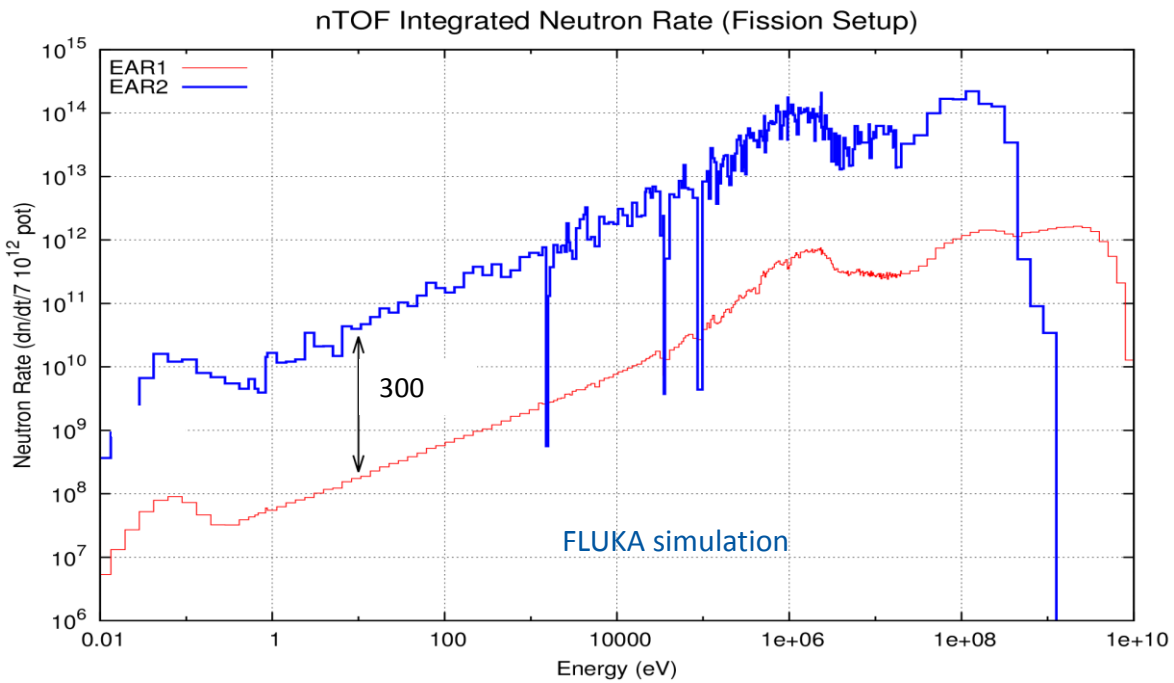
n_TOF EAR2 advantages

- Neutron fluence is on average increased by a factor of 30
- Very small mass samples (<1 mg) could be measured
- Very small cross-section
- Much shorter time scale measurement
- Running in parallel with Experimental Area 1

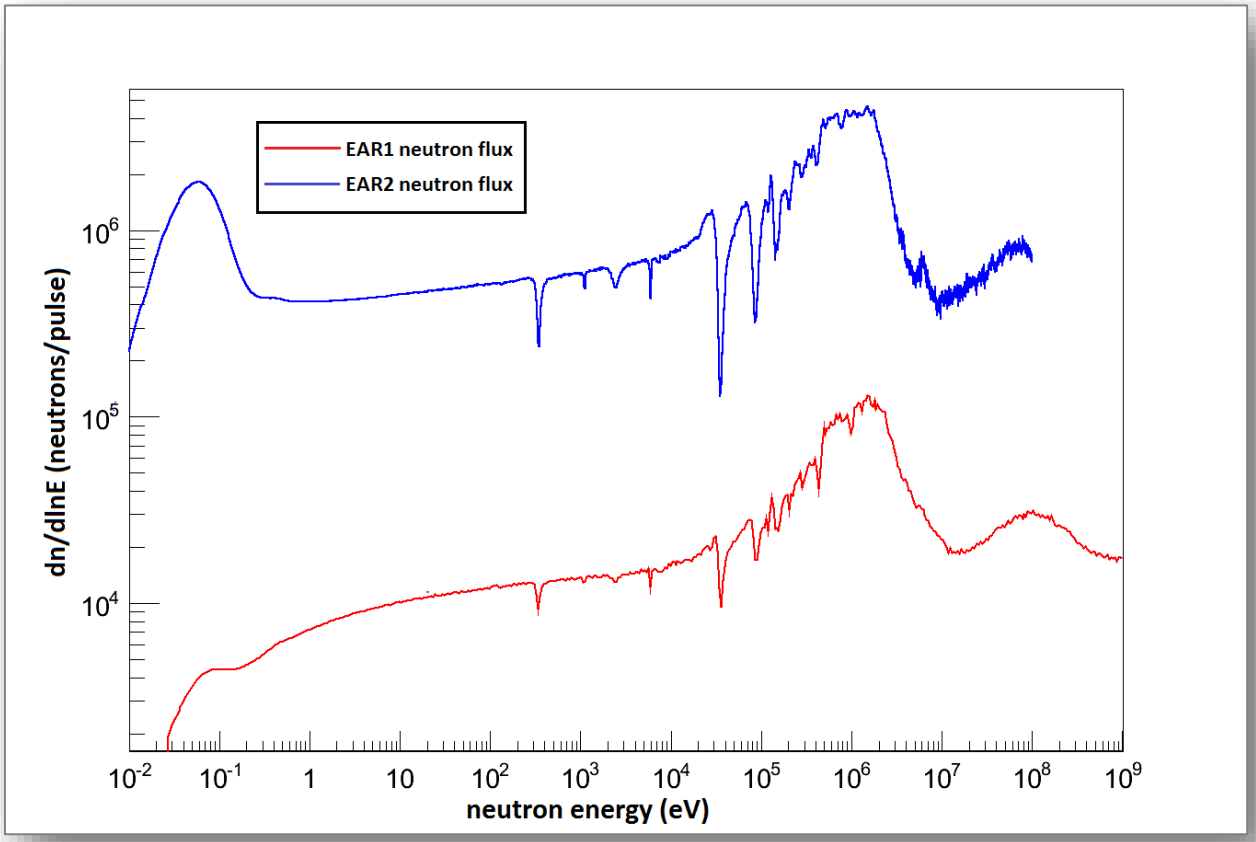
Expected neutron flux at EAR2

- 30x higher neutron flux in EAR-2 with respect to EAR-1 (FLUKA simulation)
- 10x smaller neutron time arrival (10x shorter path)

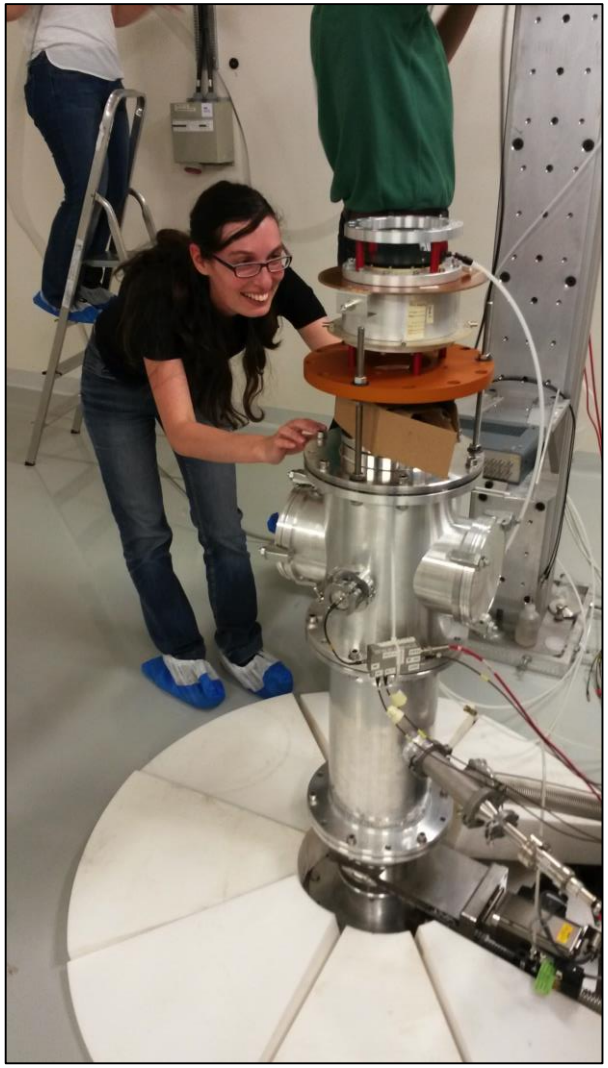
⇒ 300x times higher neutron rate

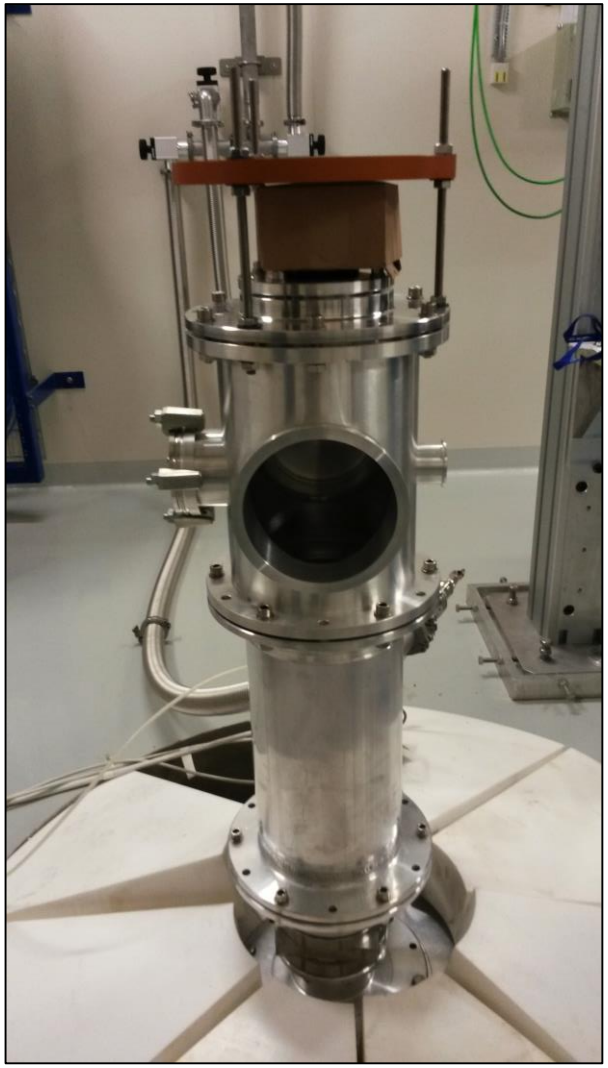


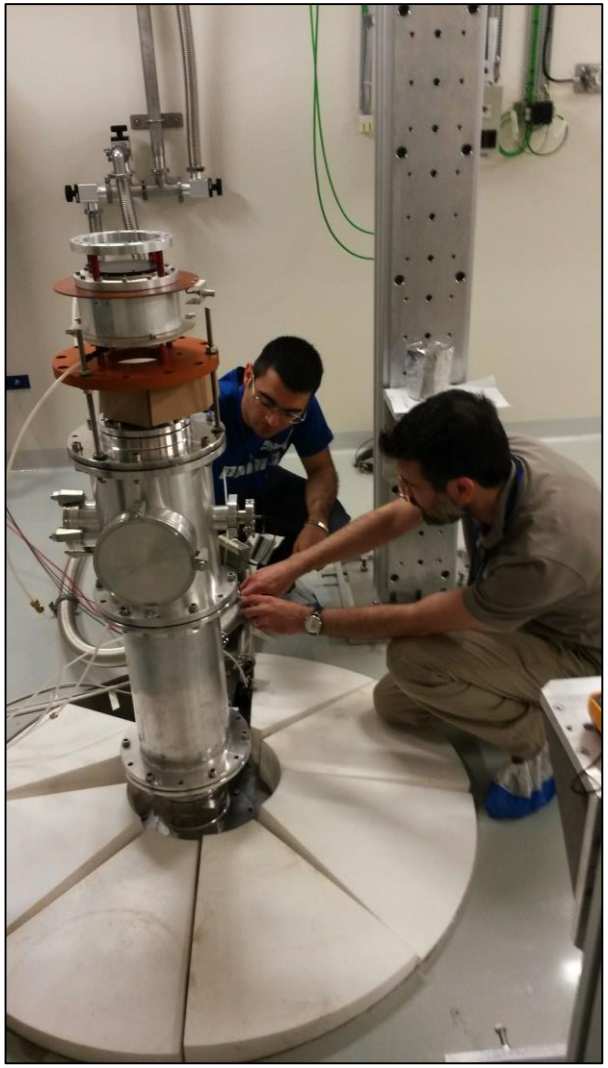
Experimental result of n_TOF Flux



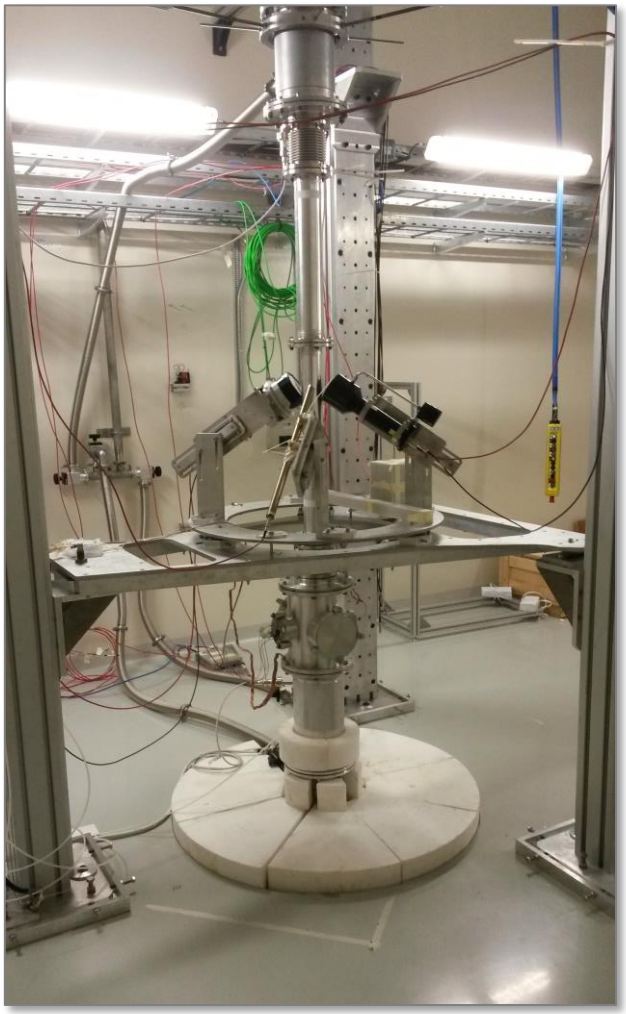
EAR2

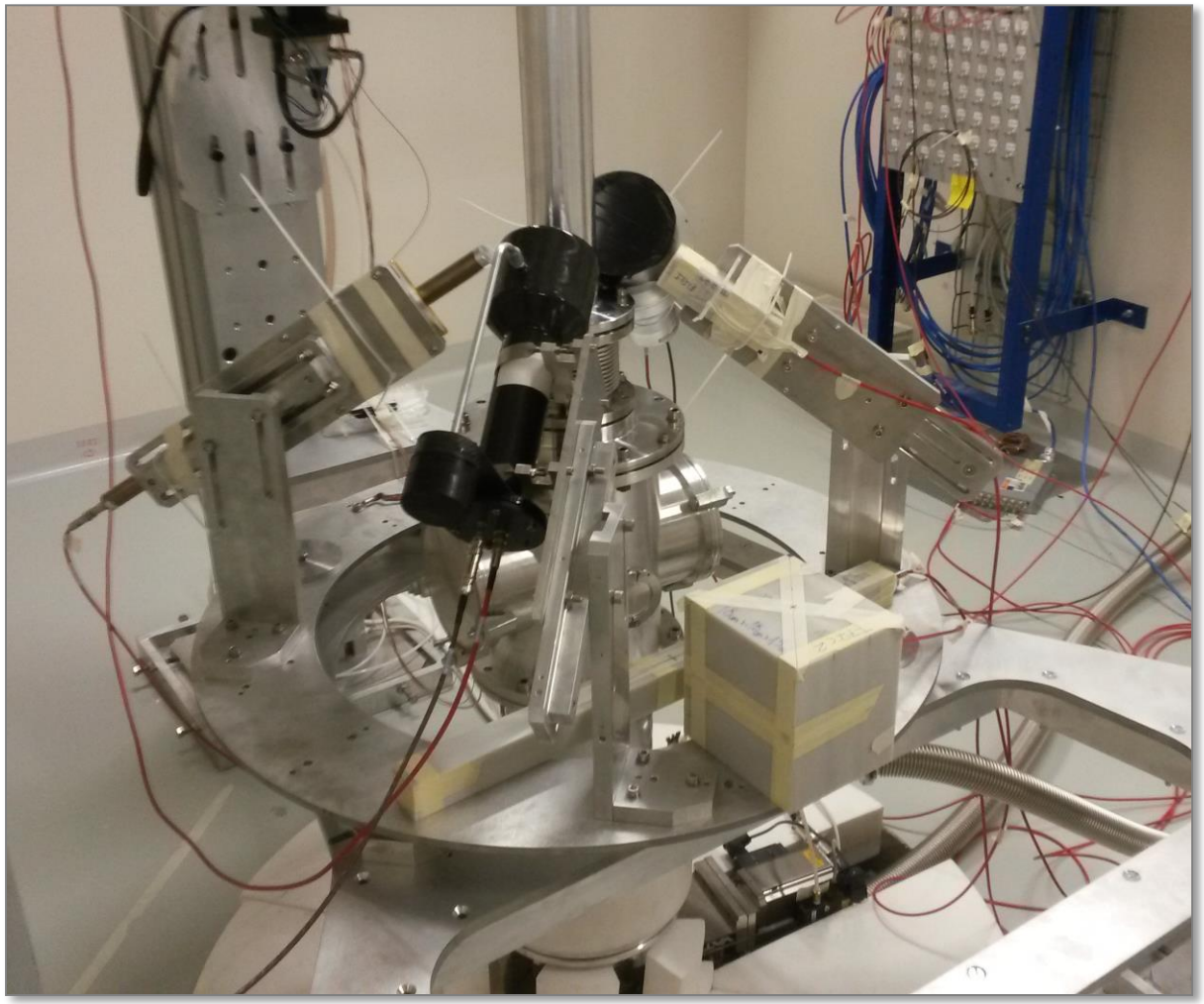






The neutron Time Of Flight Facility: EAR2






nTOF
nTOF
e dream

The Cosmological Lithium Problem

Bing Bang Nucleosynthesis (BBN), is one of the cornerstones for Bing Bang Theory.

BBN gives the sequence of nuclear reactions leading to the synthesis of light elements up to Na in the early stage of Universe (0.01-1000 sec)

BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He.

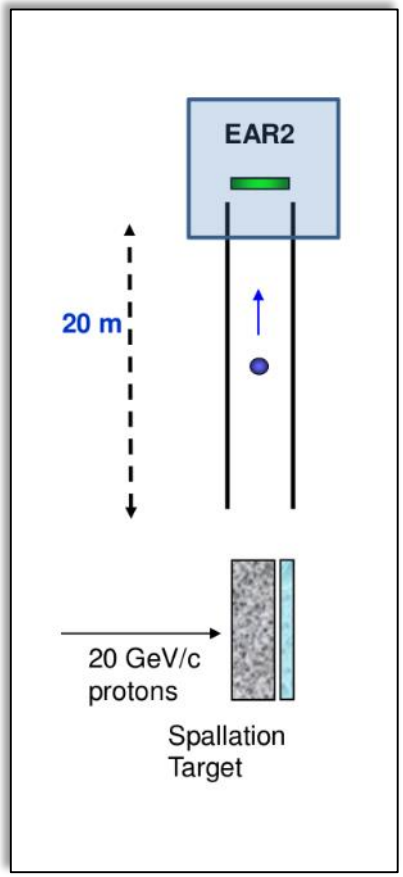
A serious discrepancy (factor 2-3) between the predicted abundance of **^{7}Li** and the value inferred by measurements → Cosmological Lithium Problem (CLiP)

95% of primordial **^{7}Li** is produced from the Electron Capture *decay* of ***^{7}Be*** (***$T_{1/2}$=53.2 d***)

A higher destruction rate of ^{7}Be can solve or at least partially explain the **CLiP.**

No direct measurement data (so far) in the neutron energy range of interest for BBN

EAR2 measurement of ^{7}Be(n,cp)



The ^{7}Be can be destroyed via:

$n + {}^{7}Be \rightarrow \alpha + \alpha$

Measured at n_TOF in 2015

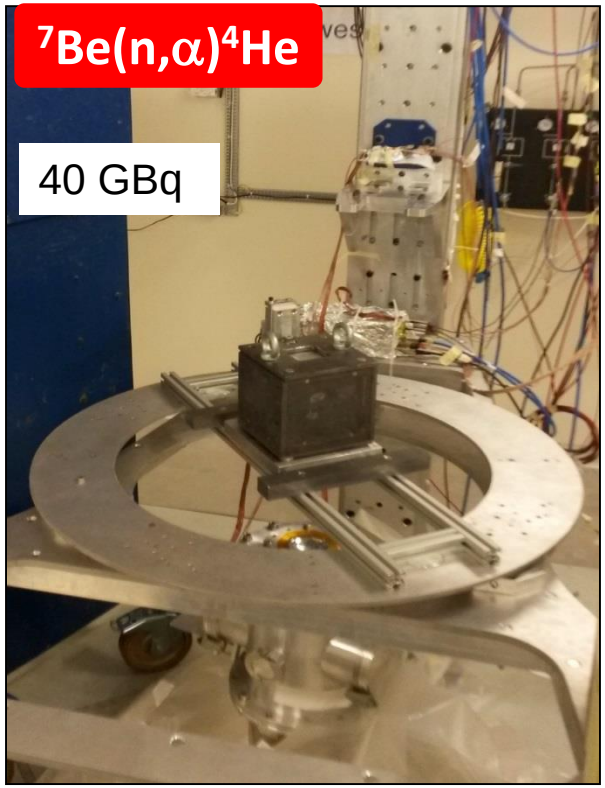
$n + {}^{7}Be \rightarrow p + {}^{7}Li$

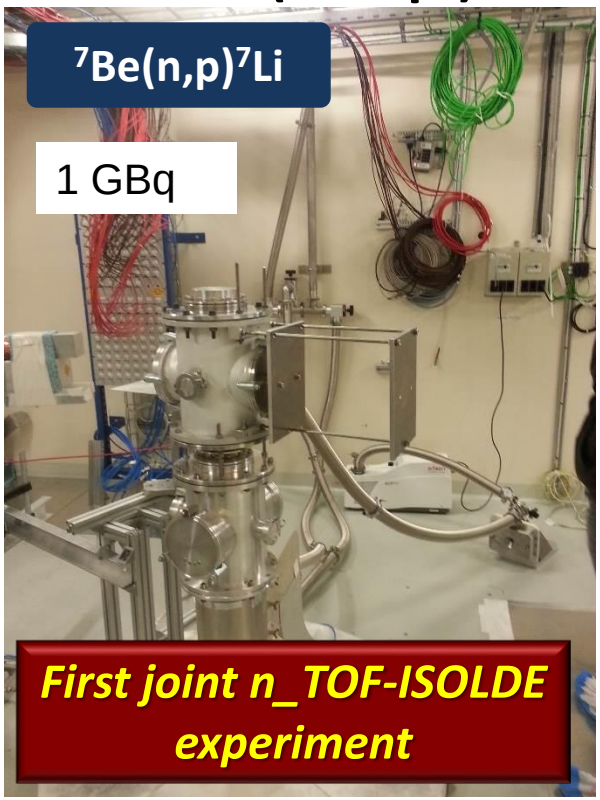
Measured at n_TOF in 2016

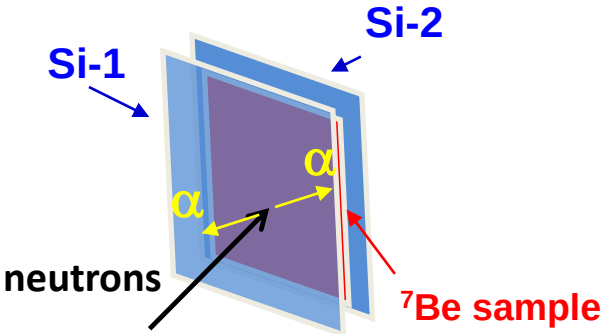
n_TOF EAR2 is a unique facility to perform such experiment as the higher flux allows to:

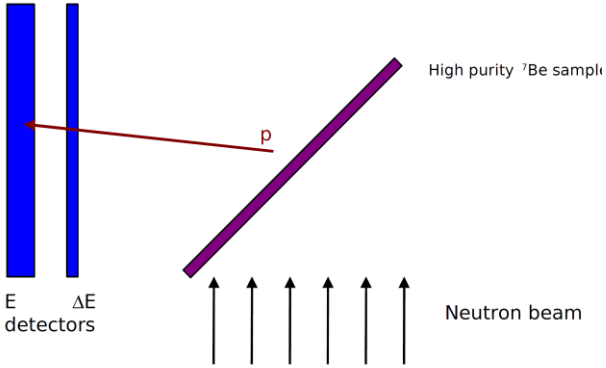
- Measure short-lived radioisotopes ($T_{1/2}$ (^{7}Be) ~ 53.2 d)
- Collect data on a much shorter time
- Measure samples of very small mass (<< 1 mg)

EAR2 measurement of ^{7}Be(n,cp)

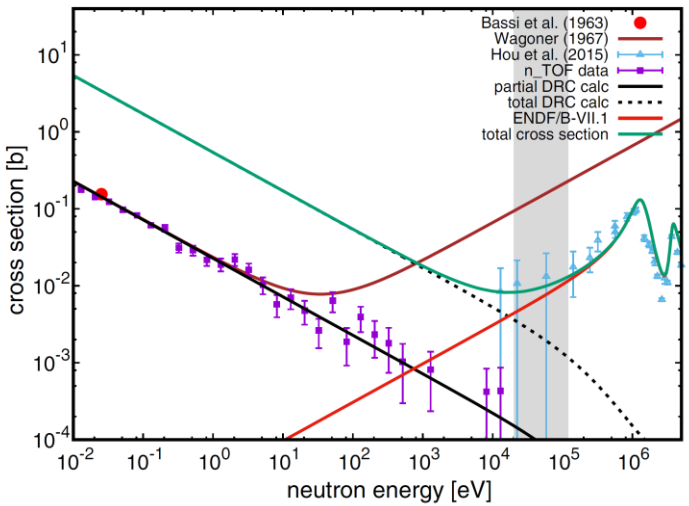


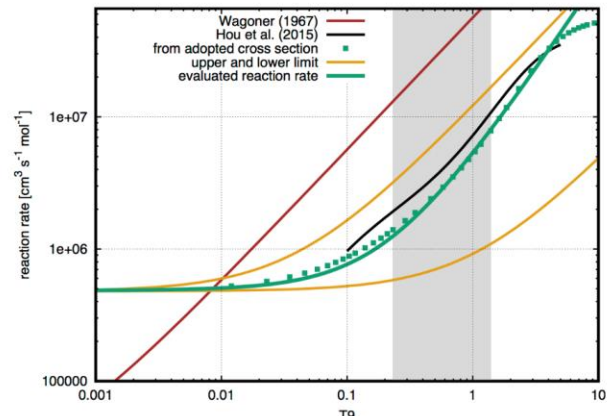






$^7Be(n,\alpha)^4He$ n_TOF results and CLiP





$$N_A\langle\sigma v\rangle = 4.81\times10^5 + 1.84\times10^6 T_9 + 3.03\times10^6 T_9^{3/2}$$

M. Barbagallo et al., Physical Review Letters 117, 152701, 2016

- http://home.cern/about/updates/2016/10/ntof-plays-hide-and-seek-cosmological-lithium
- http://home.infn.it/it/comunicazione/news/1999-il-mistero-nascosto-nei-primi-tre-minuti-di-vita-dell-universo
- http://www.astronomianews.it/index.php?p=astro_news&n=2215

As for (n,α) measurement, the Cosmological Lithium Problem worsens!
Stay tuned for (n,p)…

EAR2 measurement of ^{240}Pu(n,f)

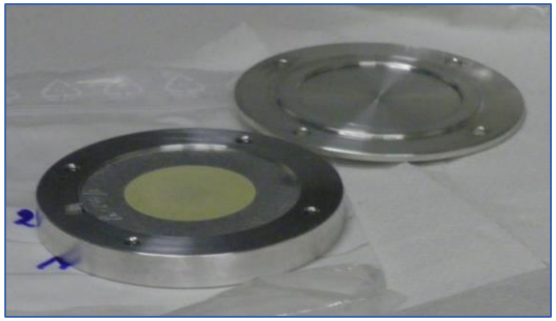
- Measurement during Phase 2 in EAR1 not successful:
  1. Detector deterioration over time (2 years!).
  2. Spontaneous fission rate – dominant in sub-threshold region.
- New measurement in EAR2:

  ⇒ Higher flux = shorter measurement time.

  ⇒ Shorter time window per pulse = signals dominate over spontaneous fission.

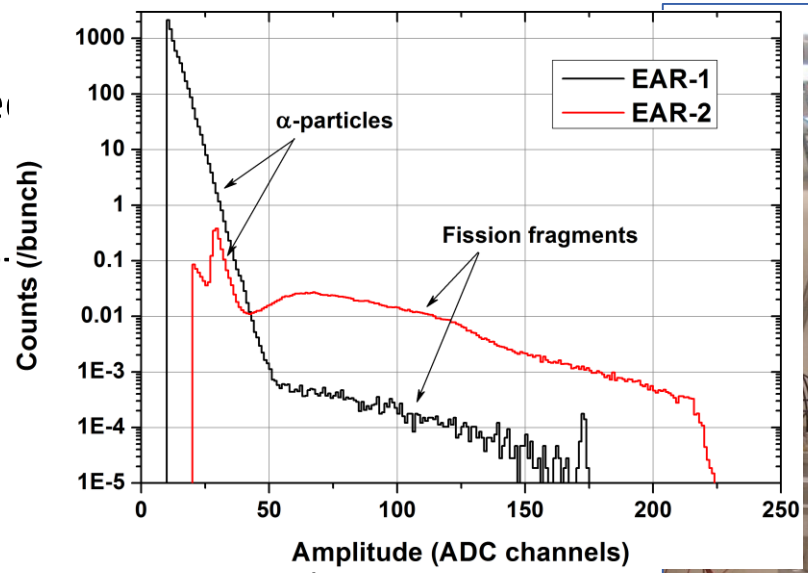
- Samples from IRMM:

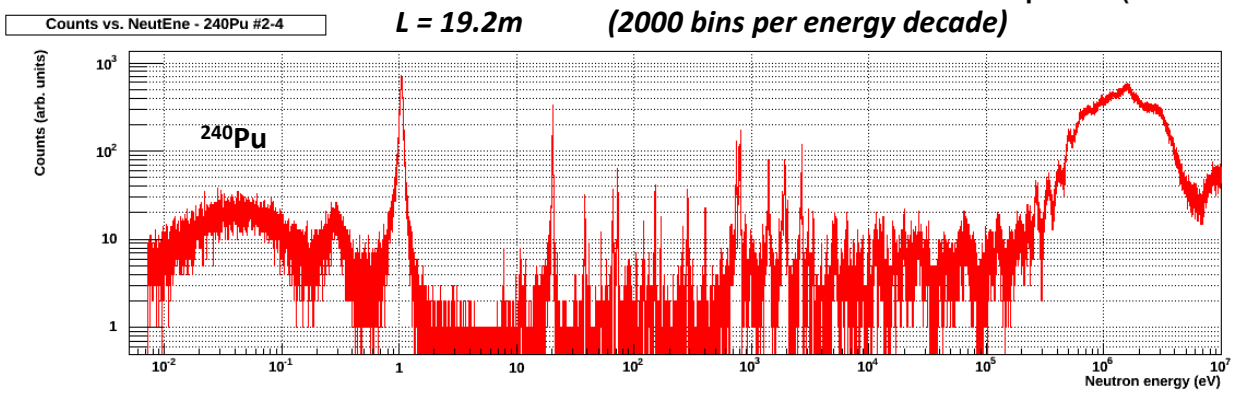
  Three $^{240}PuO_2$ (99.89%) deposits of 3 cm diameter on 0.25 mm Al backing: 25.7 MBq
- Reference samples:
  - ^{235}U (~90μg/cm^2)
  - ^{238}U (~110μg/cm^2)

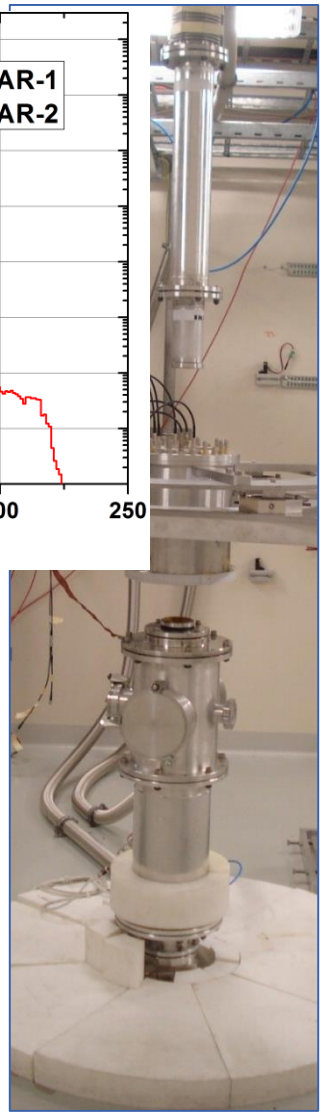


EAR2 measurement of ^{240}Pu(n,f)

- Measurement with MGAS dete
- Good α-FF separation.
- Many resonances visible in sub-threshold region.







✓ ^{240}Pu(n,f) measurement successful in EAR2!

Medical implications of $^{33}S(n,\alpha)$ reaction

- The Neutron Capture Therapy (NCT) is an experimental binary therapy which combines neutron irradiation with the nuclear reactions produced on the target.

- The isotope widely use in this therapy is ^{10}B (Boron-NCT) due to its high (n,α) cross section at thermal energies – 3827 barn at 25 meV.

- ^{33}S has been studied as target for treating superficial tumours in NCT, or as a cooperative to ^{10}B for deeper ones, with epithermal (keV) neutron beams from accelerator-based BNCT facilities.

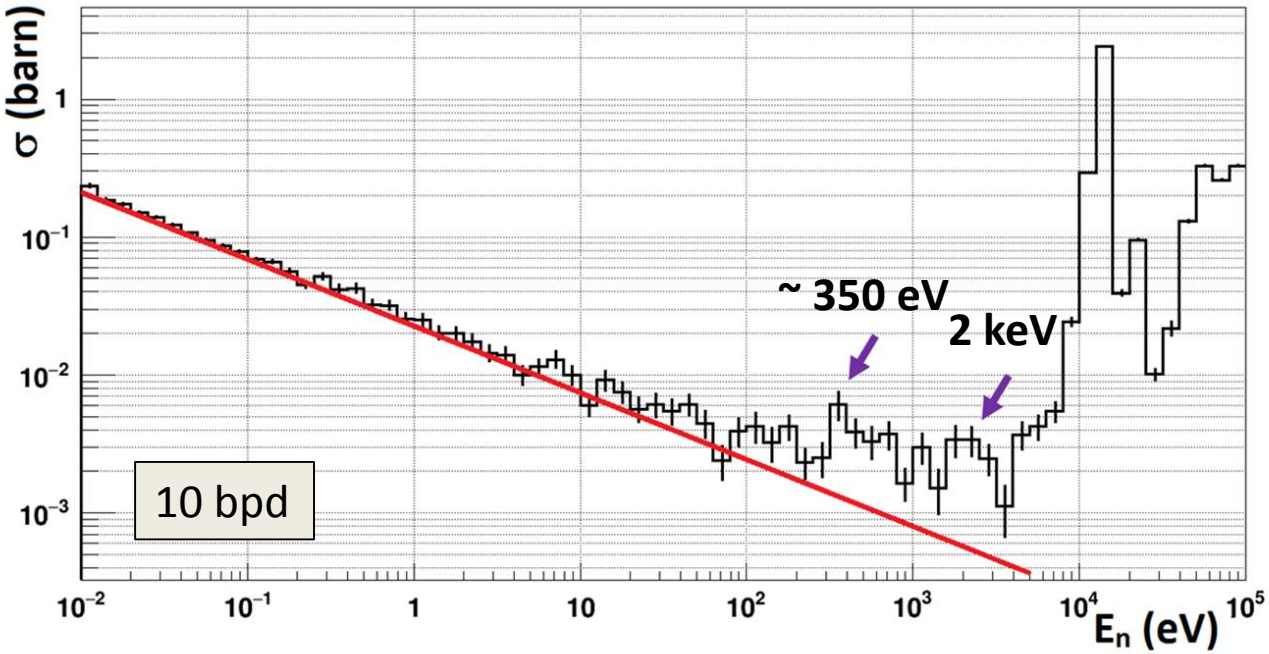
- Sulphur plays a very important biological role. High sulphur uptake has been found in many tumours by different compounds such as glutathione, thiouracil or cysteine.

Results

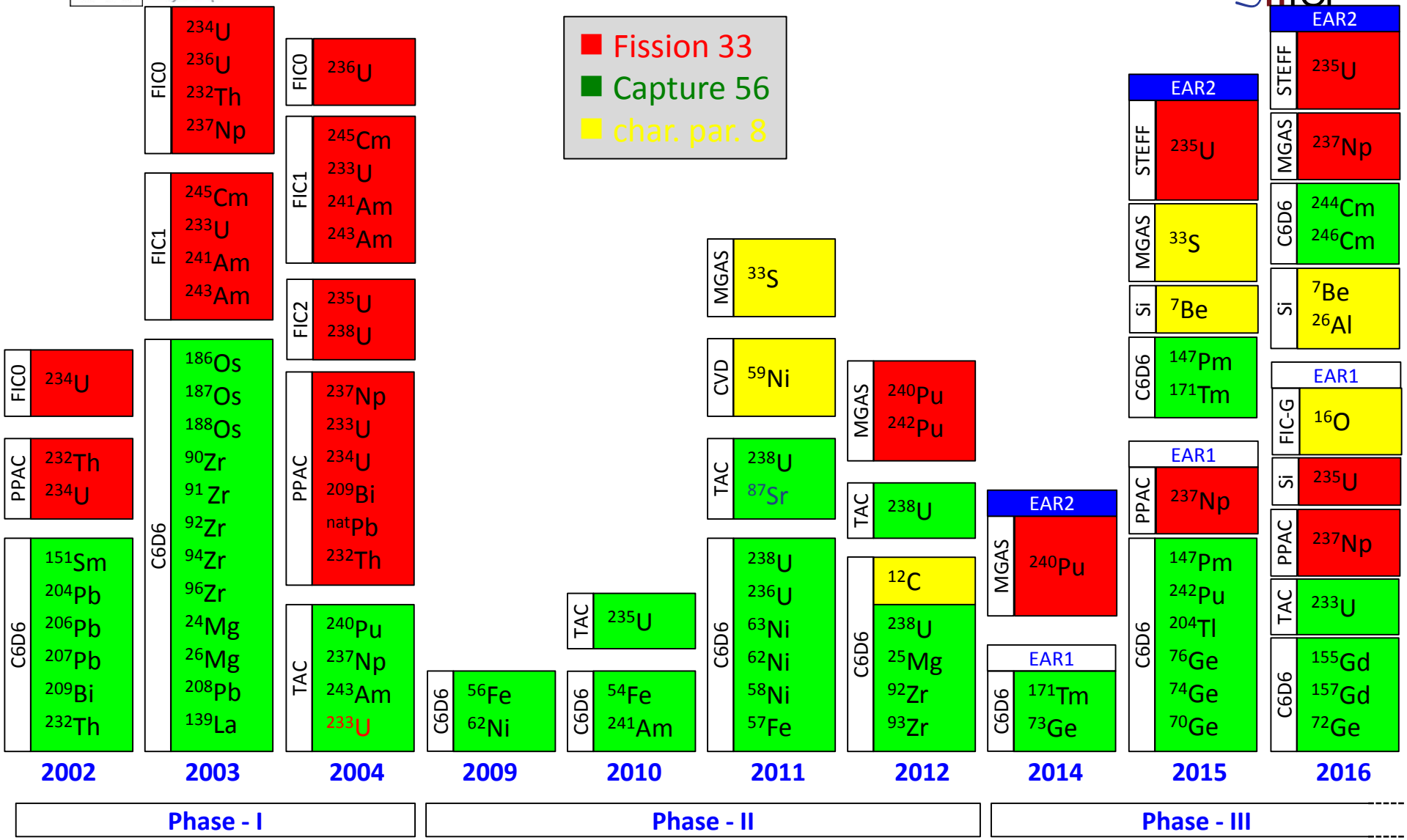
- From 1 meV up to 100 keV.
- 1/v behaviour confirmed below 10 keV:

$$y = \frac{(0.024 \pm 0.002)\ barn}{\sqrt{E_n}}$$

- For the first time the $^{33}S(n,\alpha)^{30}Si$ cross section at energies below 10 keV has been measured.



Measurements performed at n_TOF



Conclusions

- There is need of **accurate new data** on neutron cross-section both for astrophysics and nuclear technology

- Since 2001, n_TOF is contributing to the **world efforts** aimed at collecting high quality data, mostly on capture and fission

- Main advantage of n_TOF is the **high instantaneous neutron flux**, **high performance detectors , high resolution in energy , large energy range , low repetition rate**

- **Improved background conditions** in EAR1 with the borated water system

- **The new EAR2** *offers the unique opportunity to perform challenging measurements involving short-lived radioisotopes or sub-mg samples.*

n_TOF figures

117 Researchers

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n_TOF figures

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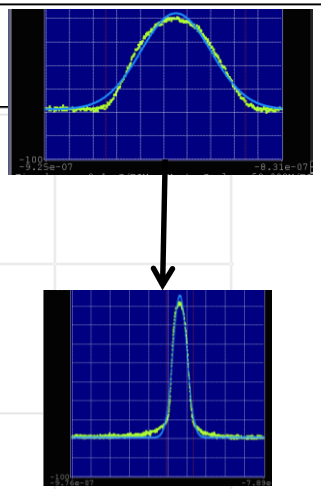
Thank you for your attention!

A bright future for neutron physics at CERN!

n_TOF beam production

n_TOF beam production: highest single bunch intensity
Issues related to single particle and collective effects

Bunch rotation before extraction

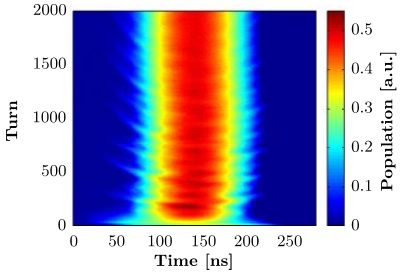


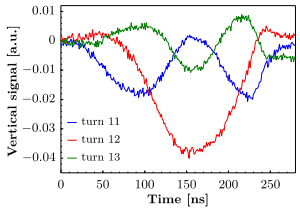
20 GeV/c

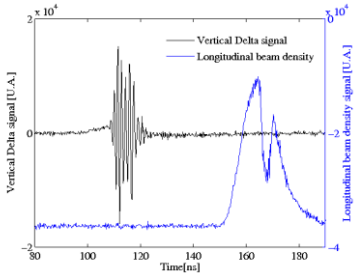
6 GeV/c

1.4 GeV

600 1000 ms





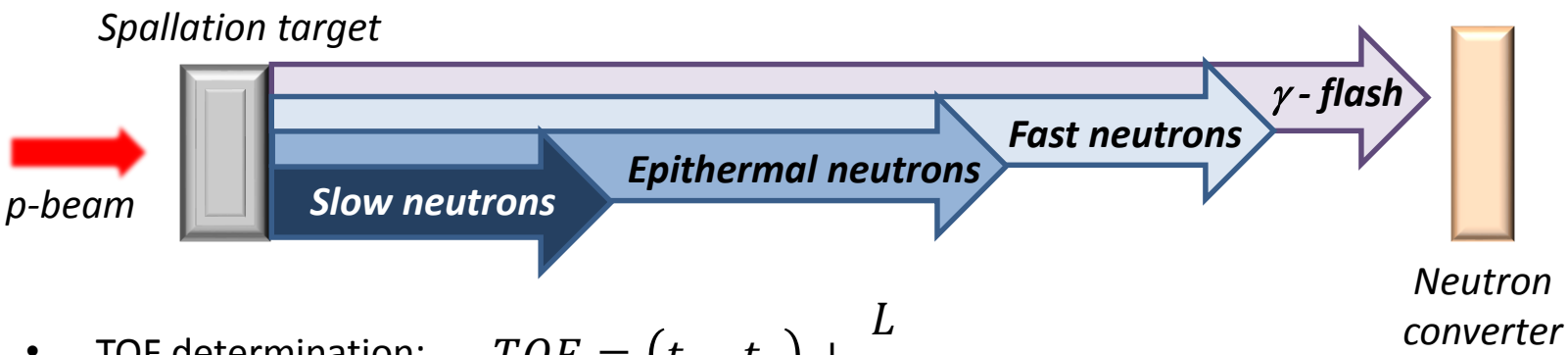


Transition crossing
Transverse mode coupling instability
Transient beam loading

Injection flat bottom:
Indirec Space charge → Injection oscillations
Transient beam loading

Time-of-flight technique

- Time-of-flight is a technique used to determine the energy of neutrons from the time that they spend traveling from the point of production to the neutron converter:



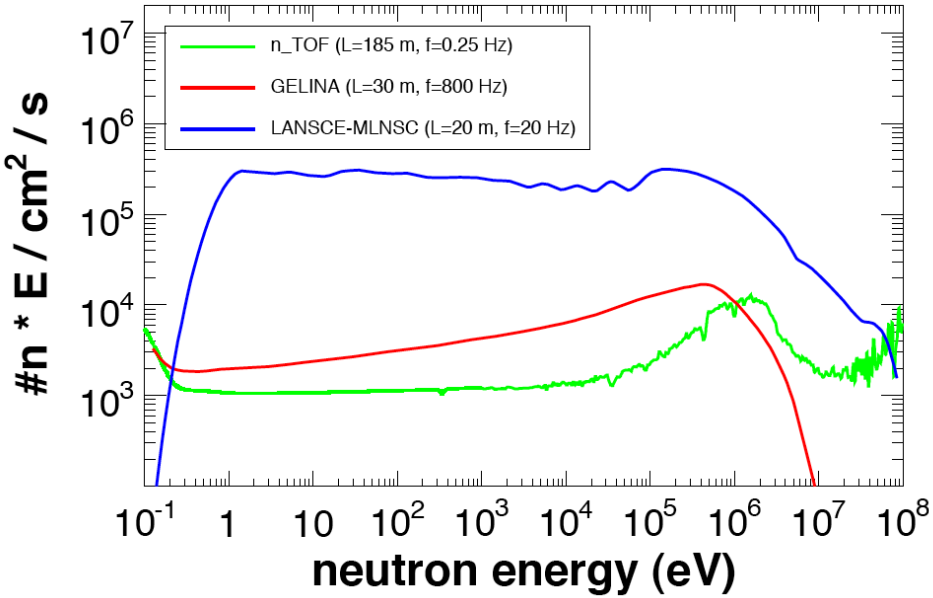
- TOF determination: $$TOF = (t - t_\gamma) + \frac{L}{c}$$

t : the arrival time of the signal to the detection system
$\boldsymbol{t_\gamma}$: the time of the γ-flash
L : the geometrical distance between the sample-converter and the spallation target
c : the speed of light

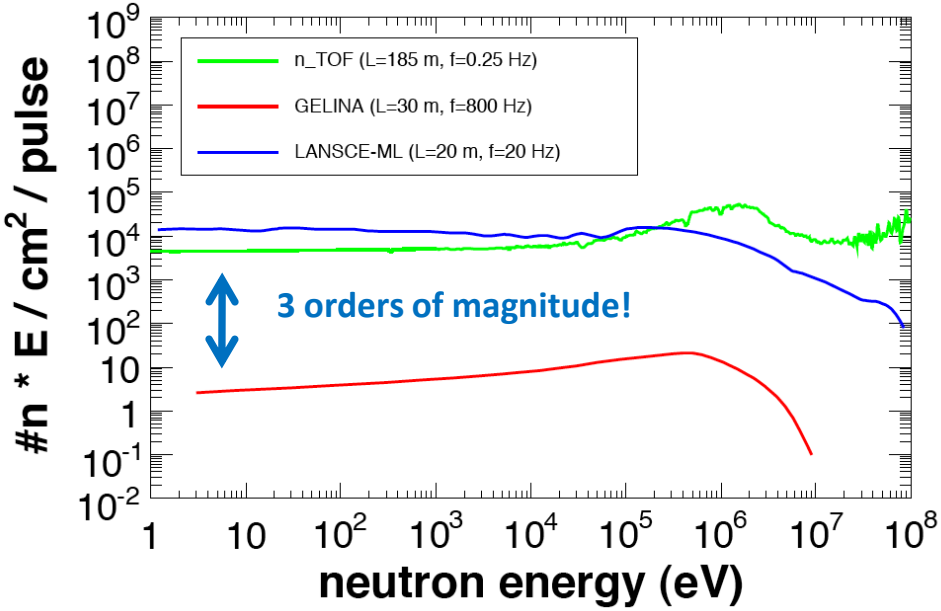
- TOF is related to the energy of the incoming neutrons by means of: $$\boldsymbol{E_n} = mn \cdot c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{L}{\boldsymbol{TOF} \cdot c}\right)^2}} - 1 \right)$$

n_TOF basic characteristics

Average flux (n/sec)



Instantaneous flux (n/pulse)

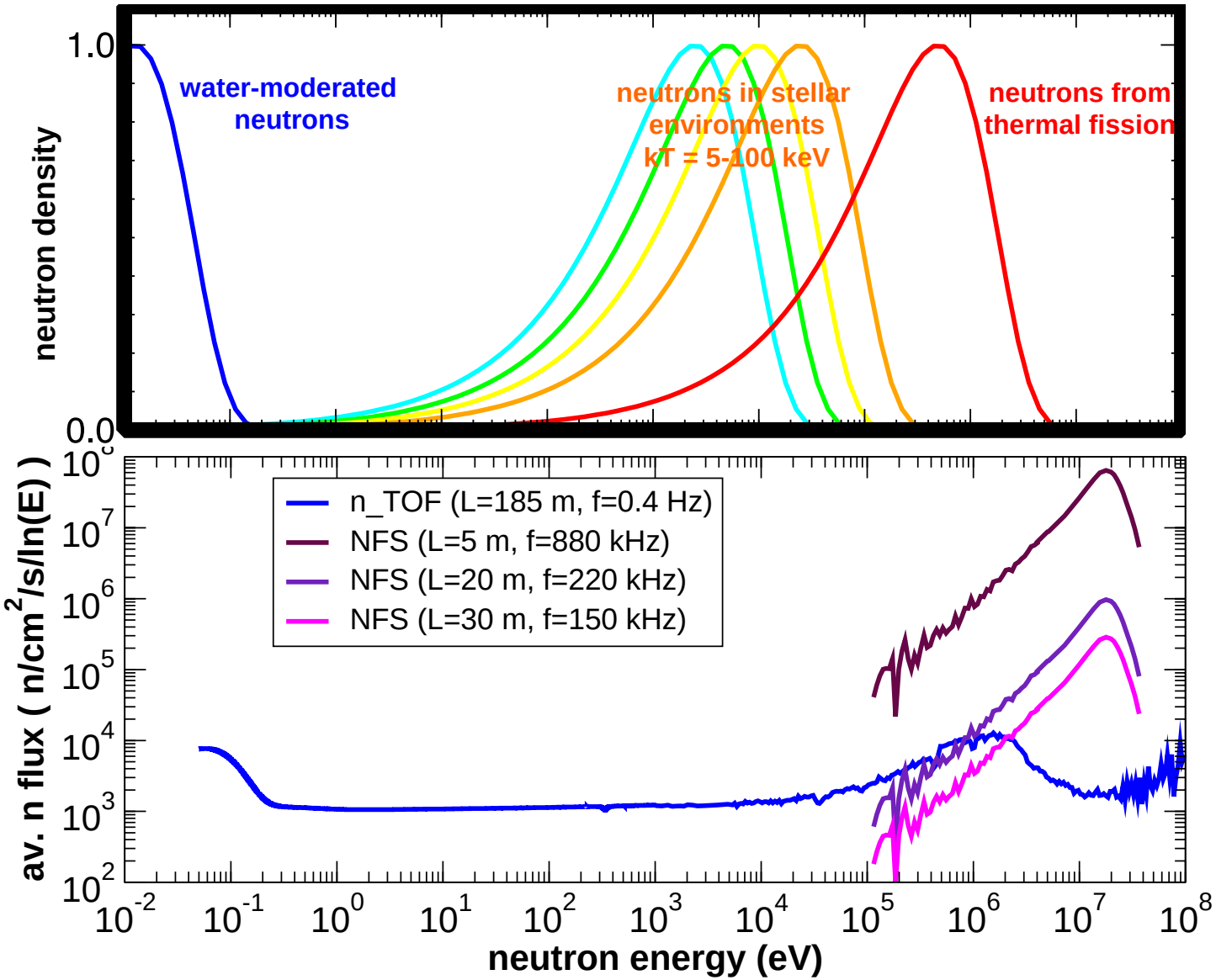


- n_TOF average flux comparable to GELINA (with 30 m flight path)

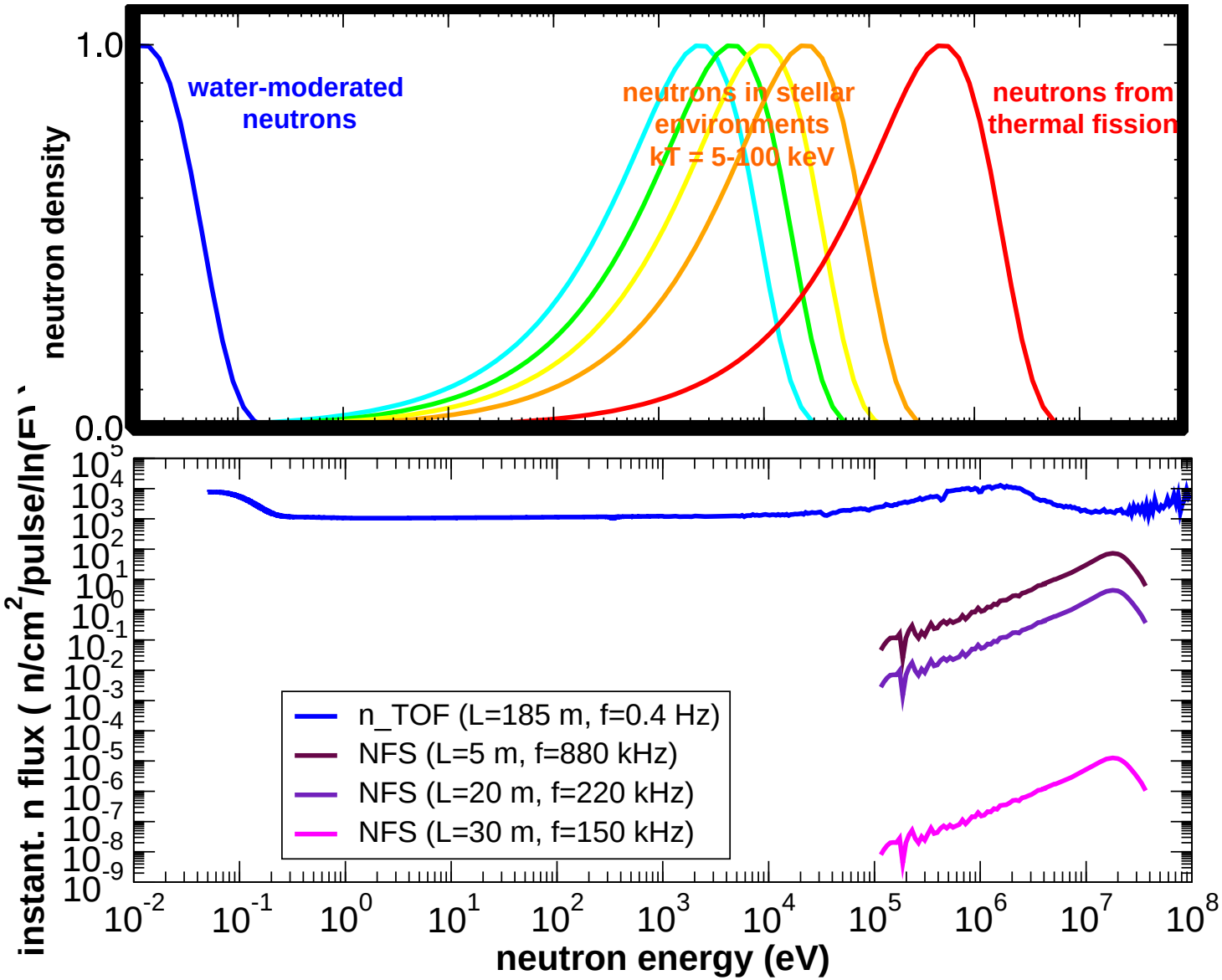
- Very high instantaneous neutron flux
  - High proton intensity per pulse
  - Spallation process

- Great advantage in measuring radioactive samples (improved S/N ratio)

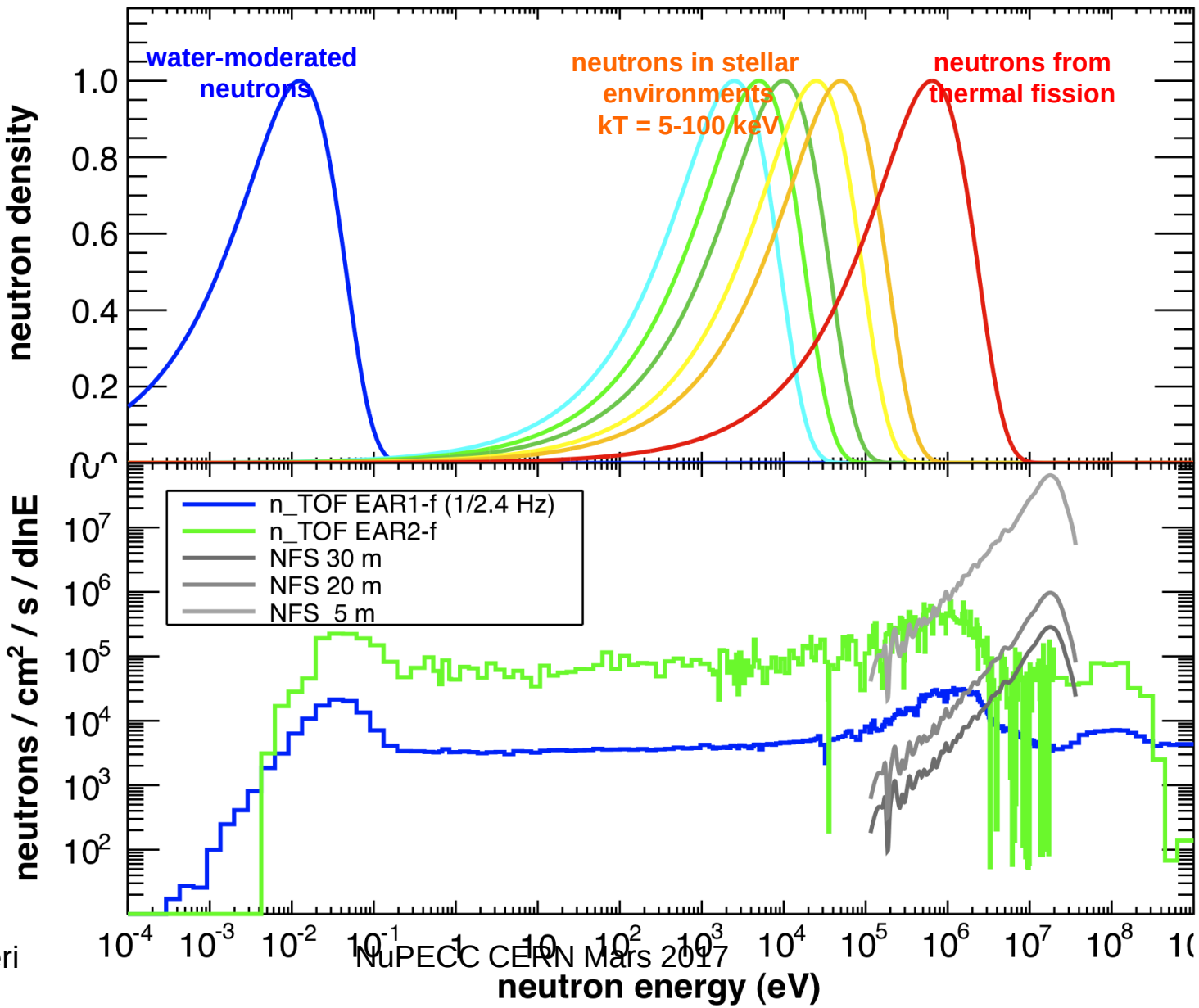
Comparison n_TOF - NFS: average neutron flux



Comparison n_TOF - NFS: instantaneous neutron flux



Comparison n_TOF - NFS: average neutron flux



Comparison n_TOF - NFS: instantaneous neutron flux